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Final Program Summary Report

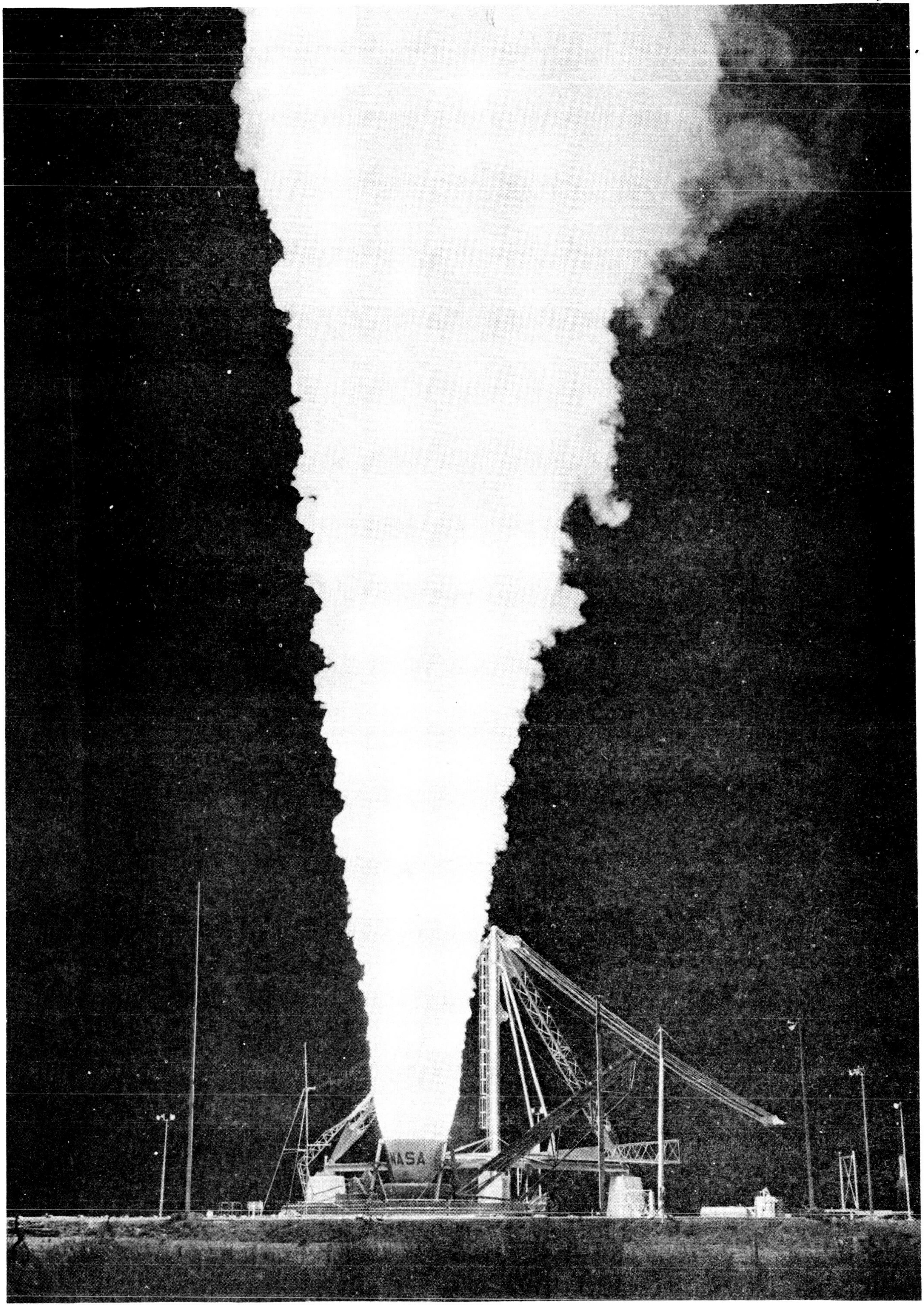
Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NO. NAS3-6284

AEROJET-GENERAL CORPORATION

SACRAMENTO, CALIFORNIA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FINAL PROGRAM SUMMARY REPORT

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8 April 1966

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Technical Management
NASA Lewis Research Center
Cleveland, Ohio

AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

FIGURE LIST

I. INTRODUCTION

The 260-In.-Dia Motor Feasibility Demonstration Program was initiated in June 1963 under the auspices of the Air Force Rocket Propulsion Laboratory as a logical advancement in the development of large solid rocket motors from the 100-in.-dia, 120-in.-dia, and 156-in.-dia motors previously tested. Program management was transferred to the National Aeronautics and Space Administration's Lewis Research Center in March 1965. The completely successful test firing of two 260-in.-dia motors under this program constitutes a major milestone in the development of solid rocketry. Significant advances were demonstrated in the extension of solid rocket technology to motors of unprecedented size.

The final report on this program consists of this summary report, together with a series of phase reports, each covering in detail a major technical element of the program. This summary report presents a review of the accomplishments of the entire program from inception through completion in April 1966.

II. THE 260-SL MOTORS

A. PERFORMANCE

The feasibility demonstration phase of the 260-in.-dia motor program was concluded with the successful static test firing of motors 260-SL-1 and 260-SL-2 on 25 September 1965 and 23 February 1966, respectively. The firing curves for motor 260-SL-1 are shown in Figure 1. The thrust was somewhat higher and the duration was correspondingly shorter than predicted due to an increase in burning rate resulting from the scale-up effect of the increased size of the propellant grain. The pressure increase that occurred just prior to tailoff was due to a processing inadequacy that occurred during casting.

II, A, Performance (cont.)

The firing results provided the means for improving performance predictions for motors of this size, and the loading process was modified for motor 260-SL-2. The results of this firing are shown in Figure 2, together with the predicted pressure.

The principal performance data given below for both motors show the high degree of performance reproducibility.

	260-SL-1	260-SL-2
Maximum thrust, lbf	3,567,000	3,564,000
Average thrust (web action time), lbf	3,144,000	3,141,000
Average thrust (action time), lbf	2,899,000	2,865,000
Maximum pressure, psia	602	601
Average pressure (web action time), psia	533	530
Average pressure (action time), psia	494	489
Web action time, sec	113.7	114.0
Action time, sec	128.2	129.8
Total impulse, lbf-sec	371,514,000	371,900,000
Propellant burning rate at 600 psia, in./sec	0.464	0.460

The 260 motor program was started under Contract No. AF 04(695)-350. The basic provisions of this contract were maintained in effect when program cognizance was transferred to the NASA Lewis Research Center on 1 March 1965. Included in the contract were performance fee-incentive provisions that were based on motor performance. Figures 3 and 4 show motor performance plotted with respect to the

II, A, Performance (cont.)

pressure envelope derived from the performance fee-incentive provisions. All performance fee-incentive provisions were met.

B. MOTOR DESCRIPTION

Figure 5 shows the basic configuration of the 260-SL motors, including the monolithic chamber, fixed nozzle, and clover-leaf grain design. The plastic components of the nozzle were fabricated from both phenolic-impregnated carbon and silica cloths. The nozzle shell was fabricated of 18%-nickel maraging steel and the exit cone support structure consisted of aluminum honeycomb with stainless-steel inner and outer facings. The motor insulation system consisted of premolded sections of Gen-Gard V-44 rubber. Aft-end ignition was used in the static test firings of the two 260-in.-dia motors.

The chamber and nozzle shell were made of 18%-nickel steel produced by the vacuum-arc-remelt process. The downhand tungsten-inert-gas welding technique was used. The fore and aft Y-rings were machined from forgings by the Ladish Co., Cudahy, Wisc., prior to delivery to the case fabricator, Sun Shipbuilding & Dry Dock Co., Chester, Penn. Forgings were also used for the forward polar flange, the nozzle attachment flanges, the throat and exit section of the nozzle shell, and for the fore and aft flanges of the exit cone. The hemispherical forward and aft heads were made by cold press forming of plate; the forward head was made in two courses and the aft head in one course. The entrance section of the nozzle shell was also made by cold press forming. The cylindrical section was made by rolling 102-in.-wide plate to a semicircular configuration, then joining two of these by two longitudinal welds. Five of these cylinders were then joined by circumferential welds to form the 510-in.-long cylindrical section. The forged-

II, B, Motor Description (cont.)

and-machined Y rings provided the transition between the heads and the cylindrical section and provided the mating surfaces for the forward and aft skirts. The pressure vessel components were designed to withstand a pressure 1.3 times maximum expected operating pressure. The nozzle shell was attached to the chamber for the hydrostatic test; a floating piston was used in the shell to transmit the force from the pressurizing fluid to the forward skirt, which also had to support the water-filled chamber. The hydrostatic test pressure was $737 {}^{+5}_{-0}$ psi.

The design of the motor case was derived from that of a full-length motor as defined by the Work Statement. Thus, the chamber wall thicknesses of 0.40 in. for the forward head and 0.60 in. for the cylinder and aft head are adequate for the full-length motor. The forward skirt is designed to react the motor weight and thrust of a full-length motor, nozzle up, and both skirts are designed to react flight loads produced by the full-length motor, including a 4-degree thrust vector control load. In addition, the bolt-circle diameter at the nozzle-chamber interface was established at 180 in., sufficient to accept the larger nozzle that would be required for the full-length motor.

Figure 5 also shows the clover-leaf grain design of the 260-SL motors. The core producing this configuration was the result of ballistics studies of the then-understood performance requirements of the full-length motor, and was designed to provide the desired grain configuration merely by fabricating additional sections.

Thus, the motor design provided the capability of being increased to any length up to that of the full length by adding cylindrical sections to the chamber, lengthening the core, and fabricating a nozzle with a larger throat and appropriate expansion ratio.

II, B, Motor Description (cont.)

The nozzle, shown in Figure 6, was fabricated (except for the 18%-nickel steel shell) by TRW, Inc., Cleveland, Ohio. Those areas of the nozzle subjected to the highest erosion were made of carbon cloth impregnated with phenolic resin. The areas further upstream and downstream of the throat area were lined with silica cloth impregnated with phenolic resin. All plastic components were overwrapped with an insulating wrap of silica cloth and phenolic and cured as individual components--the entrance section, throat, throat extension, and exit cone liner. The parts were then bonded into the structural components with epoxy resins. The nozzle entrance section was then overlaid with a premolded Gen-Gard V-44 rubber insulator that also formed a part of the step joint between the insulation in the aft head and the nozzle.

The manufacturing effort was successful except that one plastic part was rejected during fabrication of the nozzle for motor 260-SL-1. This was the throat extension, which became delaminated at the forward edge. Efforts to satisfactorily repair the part were unsuccessful, and the component was machined from the nozzle shell and replaced. As a result of the studies made of the cause of rejection of this part, the orientation of the laminations of the tape used to wrap the nozzle were modified; final tape orientations for both nozzles are shown in Figure 7.

As a result of subscale tests, the thickness of the V-44 in the nozzle entrance section of motor 260-SL-1 was increased over that originally planned to increase confidence in motor success. The thickness was returned essentially to the original design value in motor 260-SL-2. The comparative erosion of the two

II, B, Motor Description (cont.)

insulation segments were filled with V-61, which, after curing, was ground flush with the surrounding premolded segments. Fore and aft boots were installed. The aft step joint was ground to precise dimensions so that the tips of the joint were in compression with the corresponding joint in the rubber nozzle insulation. The insulation was abraded, cleaned with a solvent, and dried. The SD-850 liner was applied to a thickness of 35 ± 10 mils. The liner was then brushed to obtain final smoothness and to eliminate the small grooves left by the spacer wires on the trowels. The liner formulation is as follows:

260-SL Liner Formulation

Material	Wt%
Paracril RF-2 terpolymer (7.4 equivalents)	27.43
Methylnadic anhydride (85.5 equivalents)	17.27
Poly (1, 4-butylene) glycol (7.1 equivalents)	7.79
Diepoxide (107 equivalents)	39.89
Ferric acetyl acetonate	1.00
Ferric oxide	1.86
Silicon dioxide	4.76
	100.00

The liner was cured for two days at 80°F and then for two days at 135°F. This precure allowed the liner to gel sufficiently to prevent running or sagging. The chamber was then moved from the General Processing Building and installed in the Cast, Cure, and Test facility in a vertical, nozzle-up position.

II, B, Motor Description (cont.)

Casting of motor 260-SL-1 started on 4 June and was completed 15 June 1965. About 1,681,000 lb of ANB-3105 propellant was cast into motor 260-SL-1, of which 693,000 lb was produced by the continuous mixer and 988,000 lb was produced by the two vertical batch mixers. Following trimming of the aft end of the grain, the final net propellant weight was about 1,676,000 lb. The core was removed on 22 July following cure at 135°F, after which the grain was cooled to produce a stabilized temperature of 80°F. Net core stripping force at breakaway was 50,000 lb; the propellant surface was 500,000 sq in. The gap between the aft boot and head insulation was potted with FMC-200, an ambient-curing polysulphide rubber compound.

Casting of motor 260-SL-2 was started on 29 November and completed on 9 December 1965. About 1,678,000 lb of propellant was cast into the motor; 188 pots of vertical batch mix propellant (5500 lb/pot) and 82 pots of continuous mix propellant (8500 lb/pot). After propellant curing at 135°F and a cool-down period designed to stabilize the grain temperature at 80°F, the core was removed on 21 January 1966; net extraction force was 46,000 lb. After trimming, net propellant weight was about 1,673,000 lb. The radial deformations for the grain again agreed well with the analytical predictions. The gap behind the aft boot was potted with FMC-200.

Measured in 10KS-2500 size motors with the most precise instrumentation available at Aerojet, the propellant produces a standard specific impulse* of 244.6 lbf-sec/lbm. The density is 0.0633 lb/cu in. The tensile strength is

*Standard specific impulse is delivered specific impulse extrapolated to a motor chamber pressure of 1000 psia, a nozzle divergence half-angle of 15 degrees with an optimum expansion ratio, exhausting to 14.7 psi.

II, B, Motor Description (cont.)

in excess of 100 psi and the elongation at maximum stress is approximately 30%, which are more than adequate to meet the strain conditions in the motor. The values were determined at 77°F on samples of propellant from the pots cast into the two 260-SL motors.

Total weights for motors 260-SL-1 and -2 are shown below.

Component	260-SL-1	260-SL-2
Chamber	117,697	122,085
Forward Cap	42	42
Liner	910	908
Chamber Insulation	20,810	18,712
Insulated Chamber Assembly	139,459	141,747
Propellant	1,676,366	1,673,000
Nozzle Shell	12,536	12,725
Nozzle Liner and Insulation	14,189	13,401
Nozzle Assembly	26,725	26,126
Exit Cone	9,000	9,014
Forward Cap Bolts, Fittings, and O-rings	2.5	2.5
Nozzle Bolts and O-Ring	362.3	362.3
Exit Cone Bolts, Nuts, and O-Ring	161.5	161.5
Aft Boot Potting	6,126.5	6,487.5
V-61 Insulation	98.2	67.2
Miscellaneous Assembly Hardware	6,751	7,081
Total Motor Weight	1,858,301	1,856,968
Mass Fraction	0.902	0.901

II, The 260-SL Motors (cont.)

C. TEST FIRING

After the nozzle and exit cone were assembled to the motor and the forward cap was installed, the motor was ready for final firing preparations. A weather seal was installed in the nozzle and a continuous flow of dry nitrogen at low pressure was maintained in the motor to prevent moisture absorption. A pre-firing view of the test setup is given in Figure 9. The forward end of the motor was secured to a thrust ring supported by three 5,000,000-lbf load cells. An antiflight ring was installed around the nozzle prior to installation of the exit cone, and the igniter and its retention structure was installed. The aft-end igniter consisted of a 13-ft-long solid propellant rocket motor with a 30-in. ID. It contained 1160 lb of propellant in a case-bonded, 30-point-gear, internal-burning configuration and produced 250,000 lbf for a web action of 0.65 sec. The igniter motor is shown in Figure 10. The exhaust from the igniter achieved about a 70% bore-penetration depth in the 260-SL motor. The motor and its support structure were retained on a set of A-frames with 28 explosive bolts. Redundant pressure transducers in the forward head relayed chamber pressure to a unit that signaled release of the explosive head. Signals received from the pressure transducers were filtered so that a random signal would not prematurely release the igniter. At explosive bolt actuation, the igniter and its retention structure were released to travel up a track, propelled by igniter thrust and impingement by the 260-SL motor exhaust. The assembly was guided up the track by four wheels riding in U-beams. As the igniter reached the end of the track, a signal was generated that caused the track to be hydraulically lowered to prevent the 260-SL motor exhaust from damaging it. After the igniter and its

II, C, Test Firing (cont.)

retention structure have cleared the track, four cables attached to it, each capable of holding 220 tons, direct the assembly to the preselected impact area. Igniter motor performance and 260-SL motor ignition-interval curves are shown in Figure 11.

III. PROGRAM PROBLEMS AND THEIR SOLUTION

Although the Work Statement provided that state-of-the-art technology was to be used wherever possible, many technological advances had to be developed, principally due to the size of the motors.

A. CHAMBER FABRICATION

The first effort undertaken was to determine the methods to be used for fabrication of the large cases to the extremely close tolerances required. Prior to contract award, Aerojet had fabricated and burst two subscale 36-in.-dia pressure vessels of "Grade 250" 18%-nickel steel. The brittle failure of these cases, well below the predicted burst pressure, demonstrated that the fracture toughness of this material was so low as to make it unsuitable for reliable case fabrication. Aerojet then concentrated its efforts on "Grade 200" steel with a yield strength specified of from 200,000 to 235,000 psi at 0.2% offset. The following determinations then had to be made:

1. Steel and Weld Wire Chemistry

Since a higher percentage of the strength of the 18%-nickel steel alloy is derived from its basic composition relative to more commonly used steels, the selection of the chemistry can be critical. This class of steel is martensitic, yet it has good forming and welding characteristics, is not subject to decarburization, and can provide high strength with good toughness by a method of heat-treatment called maraging (contraction of martensitic aging) that does not require quenching.

III, A, Chamber Fabrication (cont.)

The extensive metallurgical program conducted by Aerojet resulted in the selection of an 18%-nickel steel containing 7 to 8% cobalt, 4 to 4.5% molybdenum, and fractional percentages of titanium and aluminum. Traces of boron, calcium, and zirconium were added to promote minimum grain size and to function as deoxidizers. The quantities of all other elements in the alloy were rigidly controlled to assure good weldability and maximum toughness after maraging. The same type of approach was used to select the weld wire chemistry.

2. Steel Melting Practice

Vacuum-arc-remelted steel was used throughout, both for plate and forgings. This process provides a steel with less impurities and a lesser tendency to alloy segregation in the ingots. Alloy segregation is avoided by the smaller ingot size and higher cooling rate that is produced by the vacuum-arc-remelt process. Delaminations of this nature had been found in high-nickel steel melted by other processes and could be extremely detrimental, particularly in the weld areas.

3. Welding Process

Of the various processes available, the tungsten-inert-gas (TIG) technique was selected although other common techniques were regarded as being more economical. The selection was based on the extensive experience, equipment controllability, and the high degree of flexibility associated with the TIG welding process. The TIG method also produced welds with good fracture toughness. It is believed that any faster weld-metal deposition rate provided by other methods is insignificant when related to weld setup time and quality problems.

III, A, Chamber Fabrication (cont.)

4. Heat-Treatment

Two methods of maraging were considered. One was aging the chamber in sections, then welding the sections to make a completed chamber, followed by local maraging of these welds. The other was maraging the chamber as a single unit. Because of the inability to assure that the local maraging process was adequately controllable, Aerojet elected to marage the chamber as a complete unit in a maraging furnace constructed specifically for this program. A series of tests made on samples of steel taken from plates and forgings was used to define the optimum maraging cycle. However, when a test was made in the full-size maraging furnace, using a 280-in.-dia mild steel chamber as the test article, it was found that the maraging cycle required adjustment due to the longer furnace heat-up time than was required in the laboratory. The maraging cycle was then adjusted to be one that maintained the optimum chamber temperature distribution (900°F for 8 hr).

5. Use of Forgings

Forgings were used in areas requiring precise dimensional control, difficult forming operations, or to preclude longitudinal welding of thick sections. The most significant forgings were the huge Y-rings used for the transition between the heads and cylindrical section and to provide the attachment for the skirts. Made from 26,000-lb billets, these were by far the largest ring-rolled forgings made from 18%-nickel steel, and close to the largest-diameter forgings ever made from any material. The successful fabrication of these Y-rings represented a definite advance in the state of the art in fabricating components of 18%-nickel steel.

III, A, Chamber Fabrication (cont.)

All forgings used in the 260-SL cases had very reproducible properties, comparable to those of the plate material, and strength level variation was less than that of the plate.

6. Results

The above decisions resulted in cases with the following typical values:

Yield strength at 0.2% offset, psi	225,000
Elongation at break, %	10
Reduction of area at break, %	52
Toughness, W/A, in.-lb/sq in.	1,000
Slow notch bend, G_{nc}, in.-lb/sq in.	350

Prior to fabrication of the full-size chamber components, two 36-in.-dia pressure vessels, with full wall thicknesses, were fabricated using all the materials and techniques previously selected to confirm the correctness of the design and processing-method decisions. Both vessels burst at pressures corresponding to a stress $(\frac{pr}{t})$ slightly higher than predicted, about 241,000 psi, and both were ductile failures.

B. NOZZLE MATERIALS

The Work Statement specified the use of ablative materials for the nozzle liner. While ablative components had been used extensively in smaller motors, the fabrication of nozzle components of this size was not within the bounds of current technology because of the difference in manufacturing methods, the lack of controls that would ensure the integrity of components of the sizes required, and the lack of comparable erosion data. Although all erosion data

III, B, Nozzle Materials (cont.)

considered to be potentially applicable were obtained from throughout the industry, the unproven scaling relationship limited the confidence in the resultant erosion rate predictions made for the 260-SL motor nozzles.

Another problem inherent in the large size concerned the variables that exist to a much lesser extent in smaller motor parts. For example, the smallest 260-SL nozzle liner component, the throat insert, requires 665 lb of material to be wrapped, debulked, and cured. The material being wrapped is on the mandrel at wrapping temperature far longer than that for smaller components. Holding the resin-impregnated material at the higher temperatures increases the degree of cure of the resin, making it more resistant to satisfactory debulking during high-pressure cure. The mechanical properties of the part will be lessened if the state of cure has advanced too far, with the result that the fibers may fail or delaminations will occur.

To solve these problems prior to fabrication of the full-scale parts, a three-fold program was conducted. First, every identifiable variable was listed and a program established for the control of each. Data were obtained from samples for such items as optimum tape-wrapping angle, cut and width of the tapes, tension during wrapping, and curing time, pressure, and temperature. Then, the desired levels of such material properties as percent volatiles, density, resin content, and the tensile and bending strengths of the finished, cured materials were determined for the various samples. The end product of this effort was intended to be a specification which so characterized the material that, if the materials met the specification, this would provide excellent confidence that the material would perform as predicted. This specification was completed and it has been demonstrated that its purpose has been met.

III, B, Nozzle Materials (cont.)

The next step in the program was to fabricate a half-length, full-diameter, full-thickness throat insert sized for a 120-in.-dia motor. This work enabled material evaluation and improvement of fabrication techniques and controls. A part was provided that could be used for extensive destructive tests to determine the adequacy of fabrication methods intended for use for the 260-SL motors.

The third phase of the nozzle material program consisted of a series of subscale motor firings. The most important of these was that of a 120-in.-dia motor having a nozzle fabricated in every respect as intended for use with the 260-SL motors. This firing confirmed that, except for unknown scale effects, all materials and fabrication and inspection techniques selected were adequate.

From data available from the motor 120-SS-1 firing, Aerojet was able to predict with confidence the range within which the erosion rate would be in the 260-SL motors. The required nozzle liner thickness was then determined, and the liner thickness allowance for erosion was doubled, which allowed for an average erosion rate at the throat of 8 mils/sec. Erosion in both 260-SL motors was nearly identical and fell within the range predicted.

C. INSULATION SYSTEM

For experience reasons, Gen-Gard V-44 was chosen for the chamber insulation material. Gen-Gard V-44 is a well-characterized material composed of Buna-N rubber loaded with silica and oriented asbestos fibers. With the material selected, the only problems involved were those concerned with the size of the chamber, which necessitated changes from conventional insulation installation techniques for V-44. These were principally the inability to fabricate and install the insulation components in a few sections and to final-cure the insulation in the

III, C, Insulation System (cont.)

chamber. Determination of the best materials to fill the joints between insulation that would have to be installed in segments was the main problem to be solved.

As in the case of the nozzle liner material, a design factor of two was used in determining the thickness of the chamber insulation system, neglecting the protective effect of the aft boot potting.

The fore and aft heads were each insulated with eight tapering segments, the edges mating with the sheets of V-44 used to insulate the chamber cylindrical section. Available epoxy resins were already known to provide more than adequate bond strength between the insulation and the chamber; Epon 948 and 948.2 were selected.

One advantage of the segmented-insulation approach was that, after the components had been laid up and cured, they could be thoroughly nondestructively tested prior to installation. V-joints were provided between the segments.

After preliminary screening, Germax-modified V-44 was selected for use in filling the V-grooves in the aft head and V-61, a material also similar to V-44, was selected for use in the forward-head grooves. Subscale motor firings, however, showed that erosion performance of V-61 was somewhat better than that of the Germax-modified V-44, and V-61 was used for all V-groove filling in the 260-SL motors. In the test firings, the V-61 tended to erode slightly less than the adjacent V-44. Insulation system performance in the 260-SL motors was satisfactory in all respects.

D. LINER

Development of an adequate liner presented one of the outstanding problems of the program. Conventional chemical liners had a process bonding life measured in terms of hours; due to the long casting time, the 260 liner had to

III, D, Liner (cont.)

provide a process bonding life in terms of weeks. Further, the adequacy of the bond system in motors of this size cannot be satisfactorily tested by non-destructive means.

Therefore, two approaches were followed: an effort to significantly improve the existing technology of chemical liners, and the development of a mechanically augmented liner system that would provide an essentially indefinite bonding life.

The Aerojet approach to the mechanical bonding system was to line the insulated chamber with sheets of polyester-impregnated Fiberglas honeycomb. Sub-scale and laboratory tests were conducted to determine optimum cell size and shape, and degree of cell filling by the propellant. The honeycomb was coated with a phenolic material that the propellant was intended to wet during casting to improve bonding. Adhesion of the propellant to the cell walls would provide great propellant-chamber shear strength. However, it was found that when propellant viscosity increased slightly, the cells were not filled and air was entrapped in the cells. This would prevent both realization of the shear strength of the system and adequate restriction of the propellant surface. Agitation of the surface of the propellant during casting was considered as a solution to this problem, but the difficulty of the mechanics involved in devising an effective means of agitating a constantly rising propellant surface caused this approach to be dropped. Because of these considerations, work on the mechanical liner system was stopped.

Development of the chemical liner involved the solution of problems in addition to that of the long process bonding life. The environment of the liner had to be maintained satisfactorily for perhaps a month or more with

III, D, Liner (cont.)

practicable means. Moisture is always present even under rigid environmental controls, and is an inhibitor of the bond reaction between the liner and the propellant. If the propellant-liner cure reaction is inhibited, a low-strength propellant layer at the interface results. Normally, a partially cured liner is used; however, because of the critical strength and bonding-life requirements for the 260 motors, this type of liner could not be used because it is more susceptible to contamination and loses its bondability rapidly. Another factor that had to be considered was the then unknown length of time that would be required for casting. Mixer output per hour was only an estimate, and a breakdown of any of the propellant processing equipment could cause an interruption in casting of indeterminate length. Because of these factors, consideration was given to lining the chamber as casting proceeded, but no method was ever devised for accomplishing this procedure.

The liner problems were solved by the development of a chemical liner that has a demonstrated bond life of six weeks, assuming reasonable humidity control. Further, tests demonstrated that, even if the liner was exposed to as much as 75% relative humidity for 12 days, a five-day period at low relative humidity restored essentially all of the original bonding potential.

The manner in which this liner was developed was the formulation of a material that promoted cure of the propellant as it came into contact with the liner and was compatible with the cure reaction. This compatibility was enhanced, and the bond life of the liner extended, by the inclusion of a moisture scavenger, an acid anhydride. The liner was completely cured as a result of the inclusion of a cure catalyst, ferric acetyl acetonate. This promoted cure of the propellant at the liner-propellant interface by migration of the catalyst across the bond interface.

III, D, Liner (cont.)

One 44-in.-dia motor was stored for nine months prior to firing, demonstrating the storage capability of this liner-propellant system. In addition, the liner has consistently produced bonds that exceed the cohesive strength of the propellant, and has demonstrated the long process bonding life and high resistance to contamination required.

E. PROPELLANT, GRAIN, AND CASTING

Aerojet selected PBAN propellant on the basis of its low raw-materials cost and because it was adequate in all mechanical, ballistic, and safety respects.

The size of the motor caused unusual requirements to be imposed on the propellant tailoring program. These included a viscosity limit prior to casting of 14,000 poises, maximum, and a pot life, defined as the time from completion of mixing to start of casting, of 10 hr. These requirements were in addition to the usual qualification tests such as that for liquid strand burning rate.

In conjunction with analytical predictions of strain concentrations, the propellant formulation was optimized to meet the mechanical, ballistic, and processing requirements. The grain design was arrived at within the envelope established by the Work Statement covering pressure-vs-time performance and type of grain design.

After the mechanical properties of the propellant had been firmly established, a final grain stress analysis could be made. This analysis showed that the stress concentrations at the star tips might provide an insufficient margin of safety. Therefore, the fillet radius at the base of the ray was increased, which decreased the stress concentration.

III, E, Propellant, Grain, and Casting (cont.)

The propellant system and grain design were satisfactory in all respects during both 260-SL motor firings.

The casting technique to be used was developed in conjunction with the preceding programs, as the results were mutually dependent to assure a homogeneous, monolithic grain structure that would meet all environmental requirements, including those of motor shipment and flight.

Generally, all case-bonded composite-propellant motors previously produced at Aerojet had been cast under vacuum to prevent air entrapment, and experience indicated that the casting technique used should be equivalent to that of vacuum casting. Casting through a tube with the lower end submerged in the propellant, or "bayonet" casting as it is sometimes termed, was selected.

Experiments at Sacramento, later confirmed in subscale motor processing, resulted in the use of a fabric-reinforced rubber tube with four longitudinal steel strips embedded in it to maintain constant tube length. The lower end of the tube was plugged and collapsed by pulling a vacuum. The tube then was expanded to its normal diameter by the controlled movement of propellant down the tube, the propellant flowing down the tube due to the forces of gravity and pressure applied in the propellant pot by a diaphragm on the propellant surface. Immersion depth of the tube was controlled by raising the casting pot as the propellant level in the motor rose. When the end of stand travel was reached, the tube was shortened.

Subscale 44-in.-dia motor firings demonstrated that deliberate interruptions in casting, for as long as three days, had no detectable effect on motor performance.

III, E, Propellant, Grain, and Casting (cont.)

After the casting of motor 260-SL-1, it was found that tube immersion depth was not as critical as previously believed, and the casting technique was simplified with a resultant decrease in casting time.

Visual examination of the bore surfaces of both motors after core extraction verified that no meaningful propellant folding or voids had occurred.

It is believed that one of the most significant results of the firings of the 260-SL motors is the demonstration that large, homogeneous, grain structures can readily be achieved.

The feasibility of fabricating and successfully firing full-length 260-in.-dia motors has been conclusively demonstrated.

F. CORE DESIGN AND FABRICATION

The aims of the core design were to assure that the core could be removed without damage to the grain, and that it could react the hydrostatic pressure loads at propellant cure temperature.

Three core designs were selected, sequentially, as design data and subscale motor processing results became available. The first of these was based on a core-removal technique that had been used successfully at Aerojet for several years. It consisted, at the 260 size, of applying a 4-in.-thick coating of foam over a solid core and covering the foam with a sheet of plastic. After the propellant was cast and cured, the foam would be dissolved by introduction of a solvent at the top and draining the solution off at the bottom, with the plastic sheet used to prevent the solvent from coming in contact with the propellant. The plastic sheet could be withdrawn, and the solid portion of the core could then be extracted without coming into contact with the grain surface. As the design

III, F, Core Design and Fabrication (cont.)

proceeded, however, it became apparent that the foam had marginal strength for use in this size motor and that an involved piping and gutter system would have to be installed in the foam to assure that it could be dissolved the full length of the core. Fabrication and installation of the protective membrane in a one-piece, wrinkle-free condition appeared to be extremely difficult, and it was further found, in experiments, that the material selected was not completely impervious to the solvent required and that the solvent would seriously degrade the mechanical properties of the propellant.

The next core which was designed was a complex one made to be mechanically collapsible or could be extracted in one piece. At this point in the program, Aerojet had no assurance that a core in contact with 500,000 sq in. of propellant could be extracted in one piece, and because of the long lead time involved for fabrication of the core, a final design decision was required. Fabrication was authorized of the collapsible or noncollapsible core.

During this period, data were becoming available from the 44-in.-dia subscale motor program. A solid core had been used that was coated with a silicone rubber which was then sprayed with a thin layer of DC-11 silicone grease. Breakaway core stripping forces of as low as 0.044 lb/sq in. had been obtained. While these data were encouraging, they were from motors of too small a size to be conclusive. Therefore, the core for the 120-in.-dia subscale motor was fabricated in two segments that could be removed individually if the core-stripping force would exceed that specified. The same core-release system was used. After the core in this motor was extracted in one piece with a low force, the decision was made to extract the 260-SL core in one piece.

III, F, Core Design and Fabrication (cont.)

The 260-SL core, shown in Figure 12, is aluminum, and is made in four sections. The 175,000-lb core was assembled vertically in the Cast, Cure, and Test Facility, with gaskets used at each joint to prevent extrusion of the propellant into the core. The previously proven core-release system was used. In addition to being fabricated in sections that were bolted together from the inside, each section was made up of several segments separated by longitudinal members that could be unbolted and removed individually. This method of fabrication provided the capability of removing the core piece by piece in the event it could not be stripped as a unit.

Prior to casting, the core and chamber were heated to 135°F, and casting and curing were conducted at that temperature. Following propellant cure, a cooling cycle was initiated in which 60°F air was circulated around the motor and into the core through air-circulation manifolds built into it for this purpose. The result of this cooling was that the aluminum core contracted and the propellant contracted in opposite directions. While the slight slumping of the propellant at the aft end of the motor precluded visual confirmation, calculations indicated that this dual contraction resulted in only the aft 10 ft of the propellant being in contact with the core, and that a significant gap existed between the core and the grain for rest of the length of the motor. The core stripping force for both motors, neglecting the weight of the core, was about 0.10 lb/sq in. of total propellant surface.

G. AFT-END IGNITION

The development of an aft-end ignition system for the 260 motors was a problem to the extent that there were probably less existing data than in any

III, G, Aft-End Ignition (cont.)

other program area. A step-by-step program of theoretical analysis was developed and conducted to provide the required data, which were then experimentally confirmed. An analytical model was developed by which the pressure level developed in the motor bore by the ignition motor could be predicted. Then a subscale model was constructed and cold-flow tests were conducted in which a stream of gas was injected into a sealed chamber and then a return stream of gas was caused to flow against the first, thus simulating the ignition motor firing into and igniting the larger motor.

Then small igniter motors were designed to be used for aft-end ignition of the 44-in.-dia subscale motors. The igniter-motor combination duplicated as closely as possible the system for the full-scale motor and confirmed analytical and cold-flow predictions.

The igniter motor for the 260 motors was conservatively designed so that it could be reused in static firings with a minimum of reprocessing. The only problem that arose was that the viscid propellant selected, on the basis of its demonstration in another program, could not be cast by conventional techniques in the thin web required in the internal-gear type of grain. This was solved by casting the propellant into trays, each mold containing three of the 30 gear teeth of the grain required. The outer side of each slab was then restricted, and the grain segments were individually bonded into the insulated igniter cylindrical section. This enabled a higher degree of inspection at each step of motor processing than that normally attainable.

The full-scale igniter test program consisted of five firings. First, one motor was statically test fired to verify ballistic performance and that the

III, G, Aft-End Ignition (cont.)

motor generated the required gas mass flow. Then two motors were fired into a cylindrical chamber that had been fabricated to exactly duplicate the length and free volume of the 260-SL motor bore and the entrance configuration of the nozzle. This free-volume simulator was instrumented with calorimeters, pressure transducers, and propellant patches to determine rate of pressure buildup and the heat flux to the chamber walls. The free-volume simulator was then shipped to the Aerojet-Dade Division, installed in the Cast, Cure, and Test Facility, and two igniter motors were fired to test the complete ignition system, including the ignition motor retention-and-release system.

Both the subscale motor tests and the free-volume simulator tests confirmed that all design criteria were correct and that satisfactory and reproducible ignition of the 260-SL motors could be expected.

IV. SUBSCALE MOTORS

Three 44-in.-dia motors, designated 44-SS (for subscale), were fabricated from steel chamber obtained from the Minuteman Program. New aft closures were fabricated that also served as the nozzle shells for the single, fixed, 13-in.-dia-throat nozzles. These motors were fabricated to duplicate as closely as possible the 260-SL motors. Segmented V-44 insulation was installed by the Goodyear Tire & Rubber Co., and the nozzles were fabricated by TRW Inc. with the same materials as those to be used for the full-size motors, within size limitations.

Processing of the motors was accomplished at A-DD to check out the lining and propellant processing equipment and techniques. The core configuration was a scaled-down version of that to be used for the 260-SL motors. The motors were shipped to Sacramento, where the nozzles were assembled, and test fired. An

IV, Subscale Motors (cont.)

aft-end ignition motor, retained by explosive bolts, was used that duplicated the mass flow rate, duration, and chamber pressure of the full-scale igniter motor. The successful firings of these motors confirmed, early in the program, that the basic design decisions were satisfactory.

The major subscale motor firing was that of motor 120-SS-1 on 19 September 1964. This motor was fabricated using a government-furnished case. This motor firing, conducted in the Cast, Cure, and Test Facility at the Aerojet-Dade Division, demonstrated at this significant scale that the designs, materials, facilities, and fabrication and processing techniques selected for the program were satisfactory. The pressure- and thrust-vs-time curves for this motor are shown in Figure 13, together with principal ballistic data.

The erosion rates in the aft head and nozzle entrance rubber insulation were higher than predicted. This was attributed to the flatter curvature of the elliptical aft head of the 120-SS-1 motor compared with the hemispherical aft head-nozzle shell configuration of the 260-SL chambers. However, to doubly assure successful 260-SL-1 motor performance, the thickness of the V-44 insulation in the aft end was substantially increased. Firing of this motor confirmed the original calculations of material loss rates, and the thickness of the V-44 insulation in the aft end of motor 260-SL-2 was fabricated to the reduced thickness of the original design.

V. FACILITIES

A plant was constructed in Florida specifically for the processing, casting, and static test firing of very large solid rocket motors. This plant, designated the Aerojet-Dade Division, was designed so that existing facilities would be

V, Facilities (cont.)

adaptable for transportation of loaded motors by barge to the Intracoastal Waterway and thence to vehicle launch sites. A part of the flood-control canal system that extends into the plant is shown in Figure 14, which also shows the plant location in Florida. The Aerojet-Dade Division was activated in April, 1964. Major facilities are as follows:

Building	Sq ft
General Processing	6,000
Plant Utilities	4,670
Fuel Preparation	11,500
Oxidizer Preparation	7,000
Quality Control Laboratory	8,300
Equipment Cleaning	2,400
Qualification Motor Processing	2,100
Continuous Mix	10,000
Vertical Batch Mixing Complex No. 1	6,800
Vertical Batch Mixing Complex No. 2	6,800
Instrumentation Center	950
Cast, Cure, and Test Facility	5,800
Propellant Pot Preparation	1,800

The propellant preparation, mixing, and casting capability has been demonstrated to be over 10,000 lb/hr. The size of solid-propellant motors that can be processed with present facilities is indicated by the interior dimensions of the Cast, Cure, and Test Facility; it is 150 ft deep and 52 ft in dia. It is built for the firings of full-length 260 motors and will accommodate much larger motors.

V, Facilities (cont.)

The test complex was designed with the capability of withstanding side loads due to thrust vector control and with space allocated in the control center for the instrumentation and recording devices required for static firings of 260 motors in which all accessories necessary to meet vehicle stage requirements are evaluated.

Equipment at the plant includes a 300-ton stiffleg derrick installed at the Cast, Cure, and Test Facility. This derrick (Figure 12) has the capacity to handle a full-length insulated chamber.

VI. SCHEDULES

Major program milestones are shown in Figure 15.

VII. BIBLIOGRAPHY

A cumulative list of reports prepared on the program during the period 1 March 1965 through 8 April 1966 is presented below. Reports generated prior to 1 March 1965 are documented in Report NAS3-6284 B-1, dated 10 August 1965.

A. FINANCIAL MANAGEMENT REPORTS

Report No.	Title	Date	Classification
SRO-6-5520-L-10	Financial Management Report	25 February 1966	U
SRO-6-5520-L-4	Financial Management Report	3 February 1966	
SRO-5-5520-L-95	Financial Management Report	22 December 1965	
SRO-5-5520-L-79	Financial Management Report	24 November 1965	
SRO-5-5520-L-76	Financial Management Report	16 November 1965	
SRO-5-5520-L-64	Financial Management Report	30 September 1965	
SRO-5-5520-L-53	Financial Management Report	25 August 1965	
SRO-5-5520-L-45	Financial Management Report	29 July 1965	
SRO-5-5520-L-29	Financial Management Report	6 May 1965	

VII, Bibliography (cont.)

B. MANPOWER STATUS

Report No.	Title	Date	Classification
SRO-5-3320-L-87	Manpower Status	9 December 1965	U

C. MONTHLY PROGRESS REPORTS

Report No.	Title	Date	Classification
SRO-65-5500-L-49	Monthly Progress Report on 260-in.-dia Motor Program, February 1965	10 March 1965	
SRO-65-5500-L-85	Monthly Progress Report on 260-in.-dia Motor Program, April 1965	15 May 1965	
SRO-65-5500-L-111	Monthly Progress Report on 260-in.-dia Motor Program, May 1965	15 June 1965	
SRO-65-5500-L-157	Monthly Progress Report on 260-in.-dia Motor Program, July 1965	15 August 1965	
SRO-65-5500-L-182	Monthly Progress Report on 260-in.-dia Motor Program, August 1965	15 September 1965	
SRO-65-5500-L-214	Monthly Progress Report on 260-in.-dia Motor Program, October 1965	15 November 1965	
SRO-65-3300-L-001	Monthly Progress Report on 260-in.-dia Motor Program, November 1965	15 December 1965	
SRO-66-5500-L-18	Monthly Progress Report on 260-in.-dia Motor Program, January 1966	15 February 1966	
SRO-66-5500-L-32	Monthly Progress Report on 260-in.-dia Motor Program February 1966	15 March 1966	

VII, Bibliography (cont.)

D. MONTHLY SCHEDULES

Report No.	Title	Date	Classification
SRO-65-5500-L-62	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	13 April 1965	U
SRO-65-5500-L-83	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	13 May 1965	
SRO-65-5500-L-118	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	24 June 1965	
SRO-65-5500-L-128	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	5 July 1965	
SRO-65-5500-L-155	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	6 August 1965	
SRO-65-5500-L-178	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	10 September 1965	
SRO-65-5500-L-196	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	18 October 1965	
SRO-65-5500-L-206	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	4 November 1965	
SRO-65-3300-L-5	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	13 December 1965	
SRO-65-5500-L-7	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	10 January 1966	
SRO-65-5500-L-20	Transmittal of Detailed Schedules, 260-in.-dia Motor Program	9 February 1966	

VII, Bibliography (cont.)

E. TECHNICAL NOTES

Report No.	Title	Date	Classification
NAS3-6284-TN-7	260-in.-dia Motor Feasibility Demonstration Program Quarterly Technical Note, 1 January through 31 March 1965	21 April 1965	C
NAS3-6284-TN-8	260-in.-dia Motor Feasibility Demonstration Program Quarterly Technical Note, 1 April through 30 June 1965	21 July 1965	U
NAS3-6284-TN-9	260-in.-dia Motor Feasibility Demonstration Program Quarterly Technical Note, 1 July through 30 September 1965	21 October 1965	C
NAS3-6284-TN-10	260-in.-dia Motor Feasibility Demonstration Program Quarterly Technical Note, 1 October through 31 December 1965	21 January 1966	U

F. TEST PLANS

Report No.	Title	Date	Classification
SRO-65-5500-L-99	Hydrostatic Test Plan, Motor Chamber 260-SL-2	20 May 1965	U
SRO-65-5500-L-119	Test Plan for Static Firing of Motor 260-SL-1	25 June 1965	U
SRO-66-5500-L-11	Test Plan for Static Firing of Motor 260-SL-2	20 January 1966	U

G. TEST RESULTS

Report No.	Title	Date	Classification
NAS3-6284 FTR-4	Final Test Report, Motor 44-SS-3	24 March 1965	C
SRO-65-5500-L-91	Final Report on Hydro-Static Test of 260-SL-1 Motor Chamber and Nozzle Shell	14 May 1965	U
SRO-65-5500-L-91	Final Report on Hydro-Static Test of 260-SL-2 Motor Chamber and Nozzle Shell	10 November 1965	U

VII, G, Test Results (cont.)

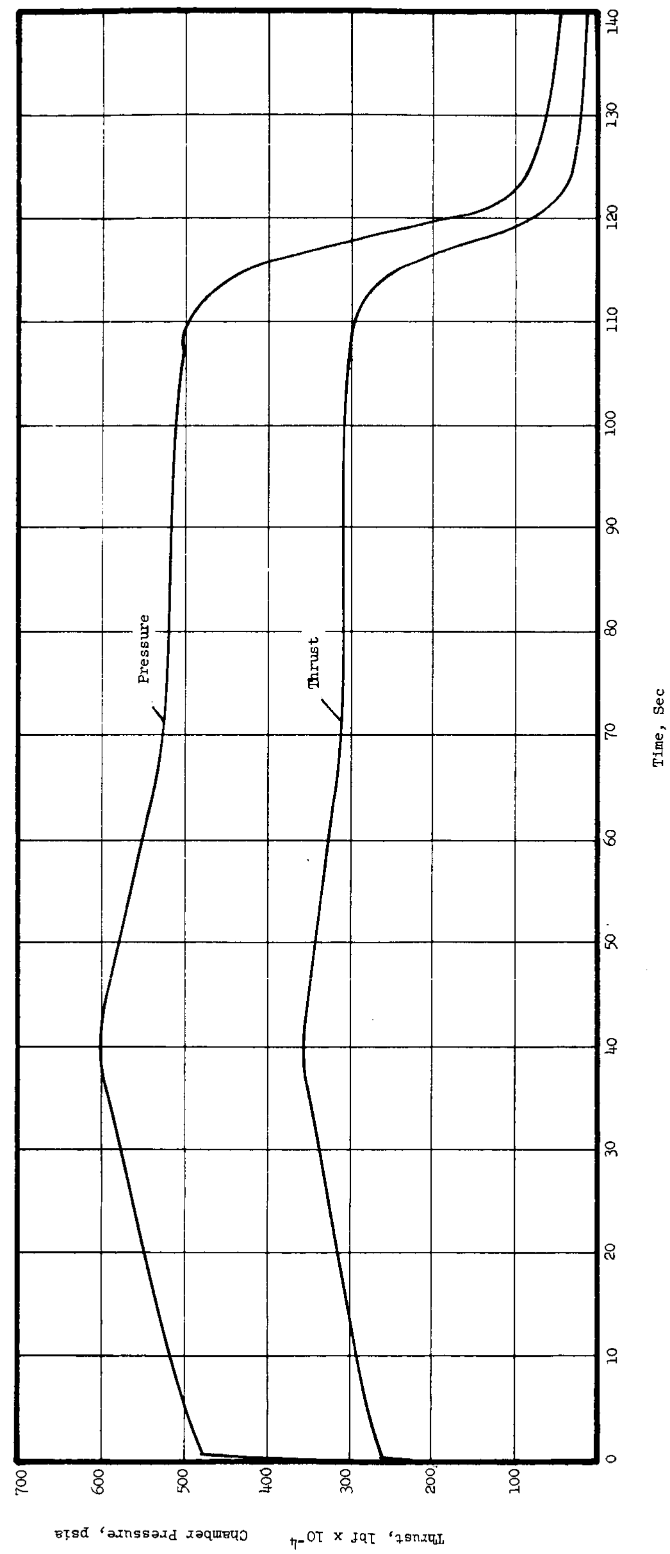
Report No.	Title	Date	Classification
NAS3-6284 FT-5	Final Report, Static Test Firing of Motor 260-SL-1	25 October 1965	C
NAS3-6284 FT-6	Final Report, Static Test Firing of Motor 260-SL-2	25 March 1966	C

H. BIBLIOGRAPHY

Report No.	Title	Date	Classification
NAS3-6284 B-1	Bibliography of Research and Development Reports	10 August 1966	U

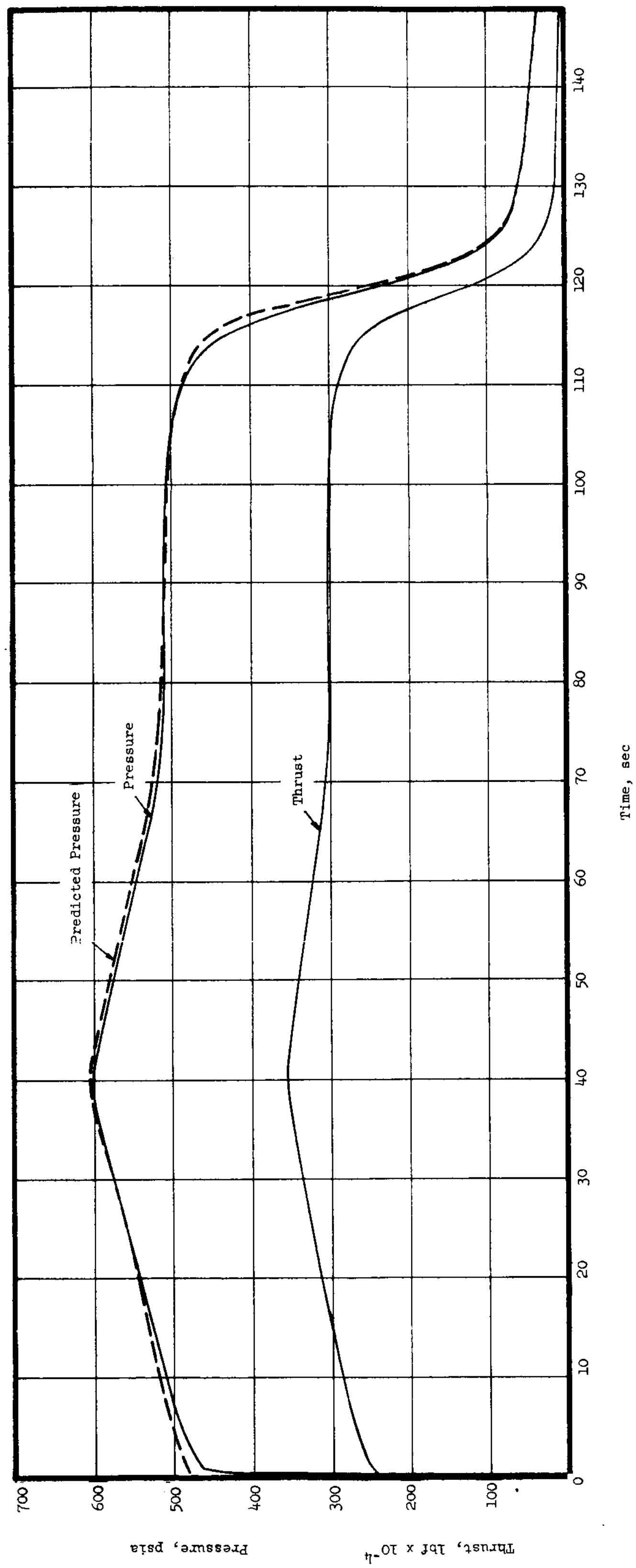
I. FINAL REPORTS

Report No.	Title	Date	Classification
NASA CR 54454	260-in.-dia Motor Program, Volume I: 260-SL Motor Aft-End Ignition System Development	20 August 1965	U
NASA CR 54473	260-in.-dia Motor Program, Volume II: 260-SL Motor Propellant Tailoring and Liner Development	19 November 1965	C
NASA CR 54925	260-in.-dia Motor Program, Volume III: 260-SL Motor Grain Design and Performance Analysis	8 April 1966	C
NASA CR 54930	260-in.-dia Motor Program Volume IV: 260-SL Motor Internal Insulation System	8 April 1966	U
NASA CR 72126	260-in.-dia Motor Program Volume V: 260-SL Motor Chamber and Nozzle Shell Fabrication of 18%-Nickel Maraging Steel	8 April 1966	U
NASA CR 72125	260-in.-dia Motor Program Volume VI: 260-SL Motor Nozzle and Exit Cone Assemblies	8 April 1966	U



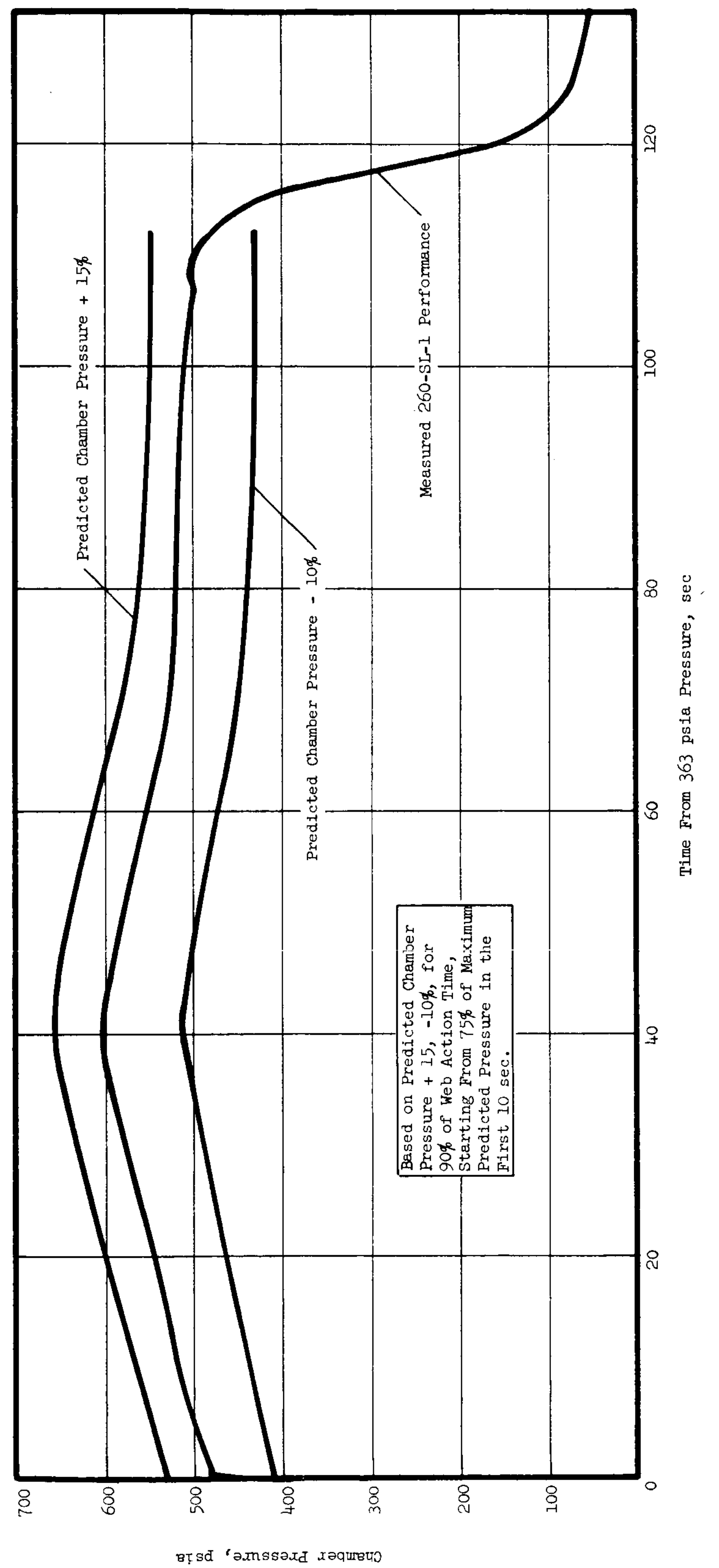
Pressure- and Thrust-vs-Time Curves, Motor 260-SL-1

Figure 1



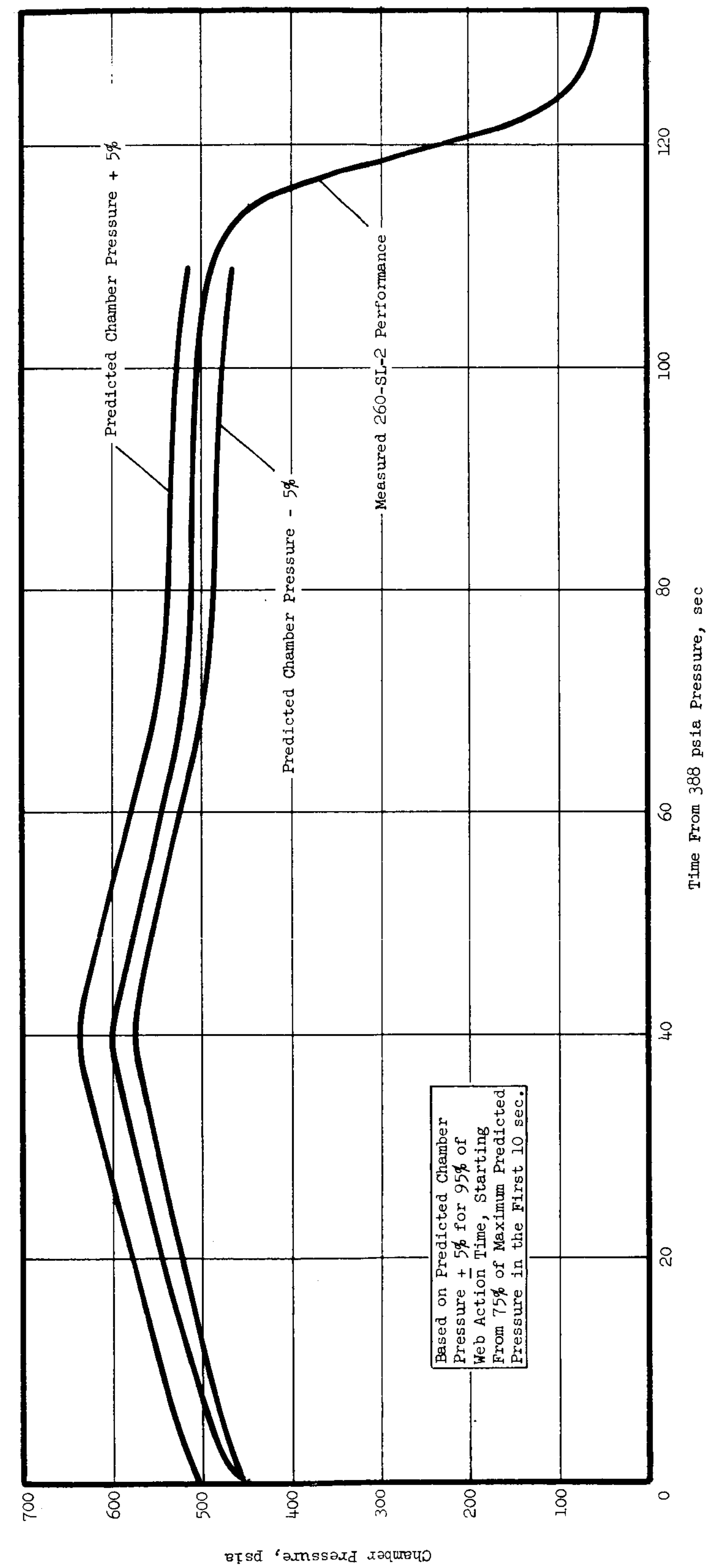
Pressure- and Thrust-vs-Time Curves, Motor 260-SL-2

Figure 2



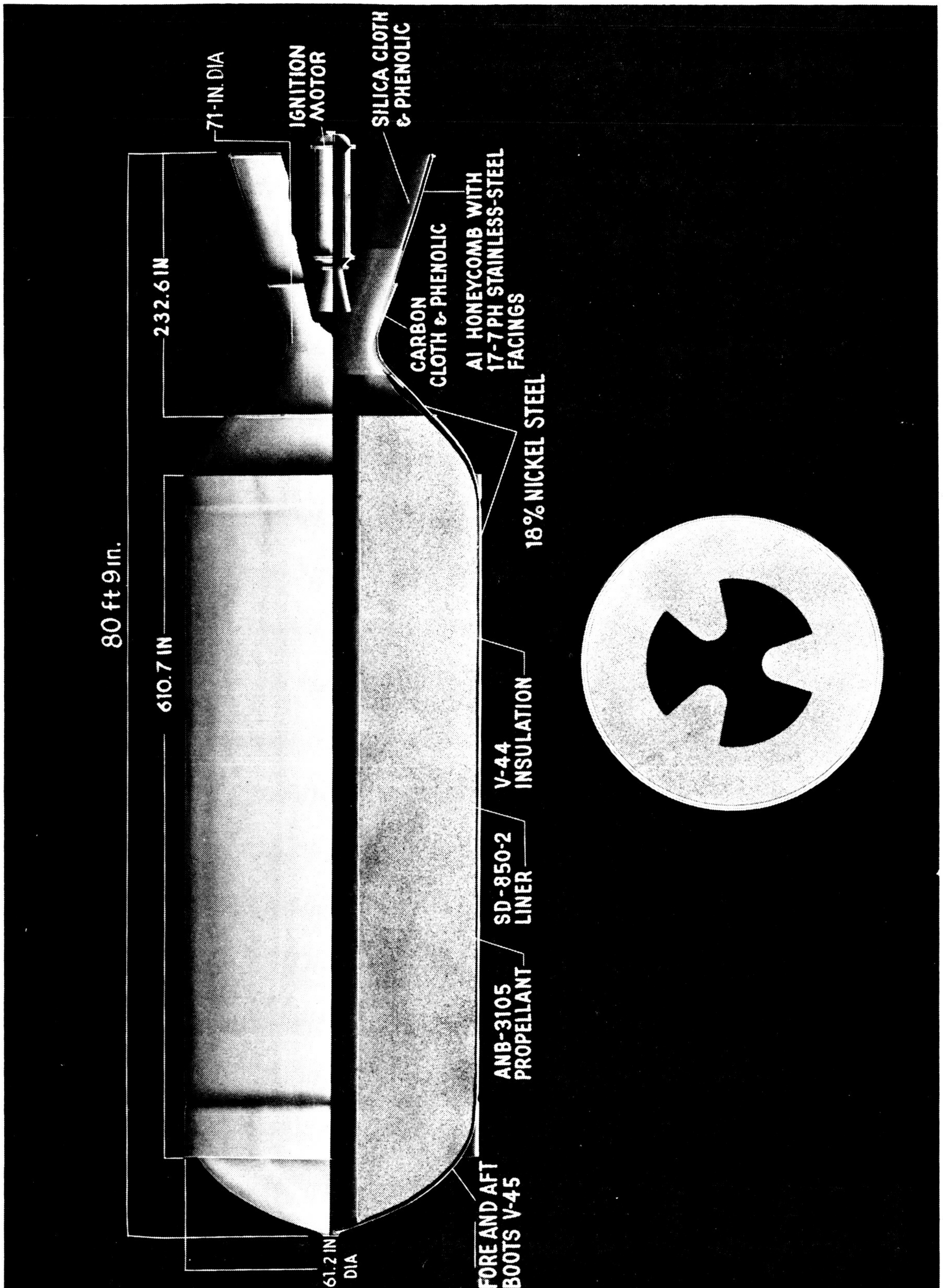
Motor 260-SL-1 Performance Plotted with Respect to Contract Requirements

Figure 3



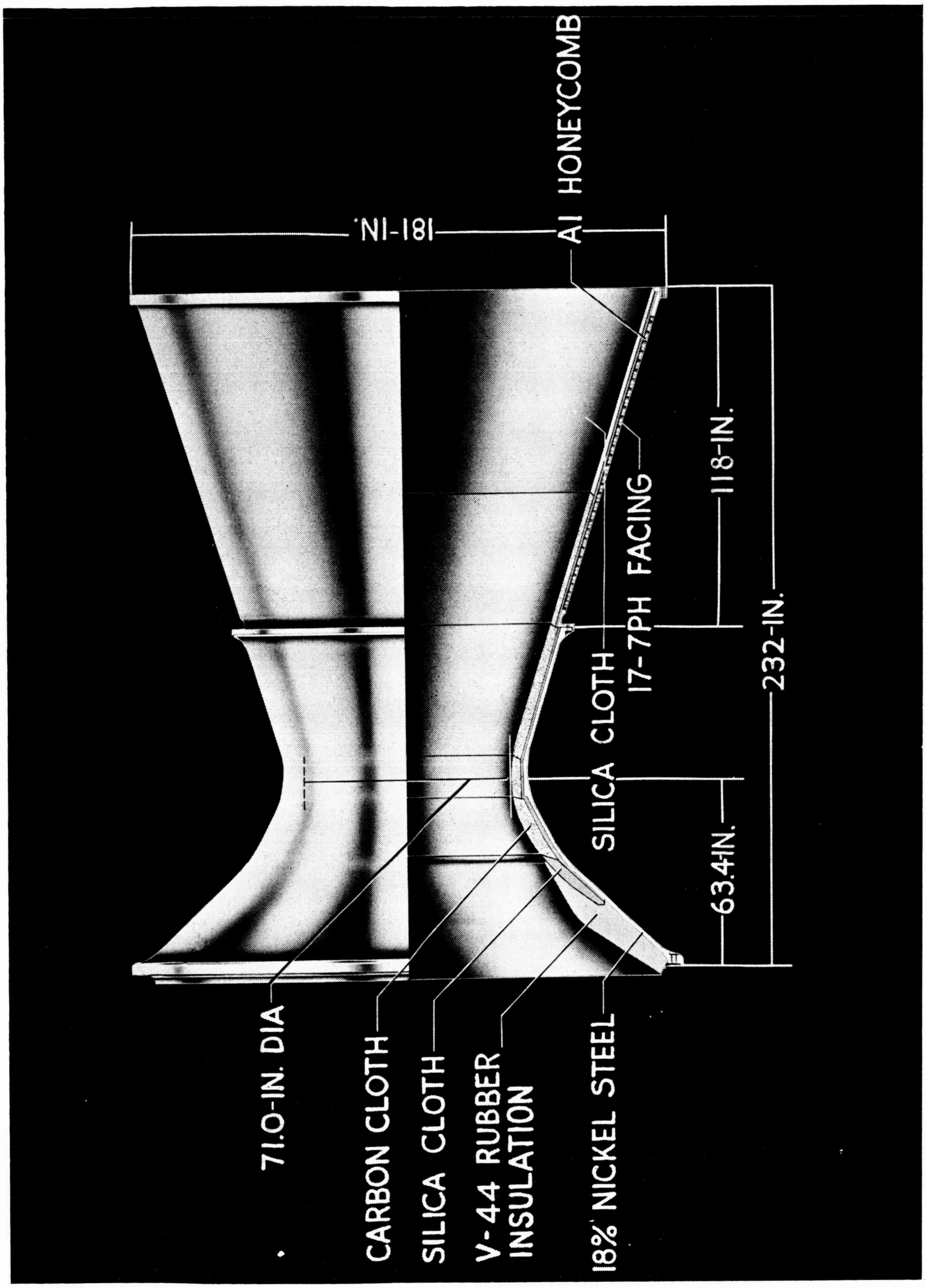
Motor 260-SL-2 Performance Plotted with Respect to Contract Requirements

Figure 4



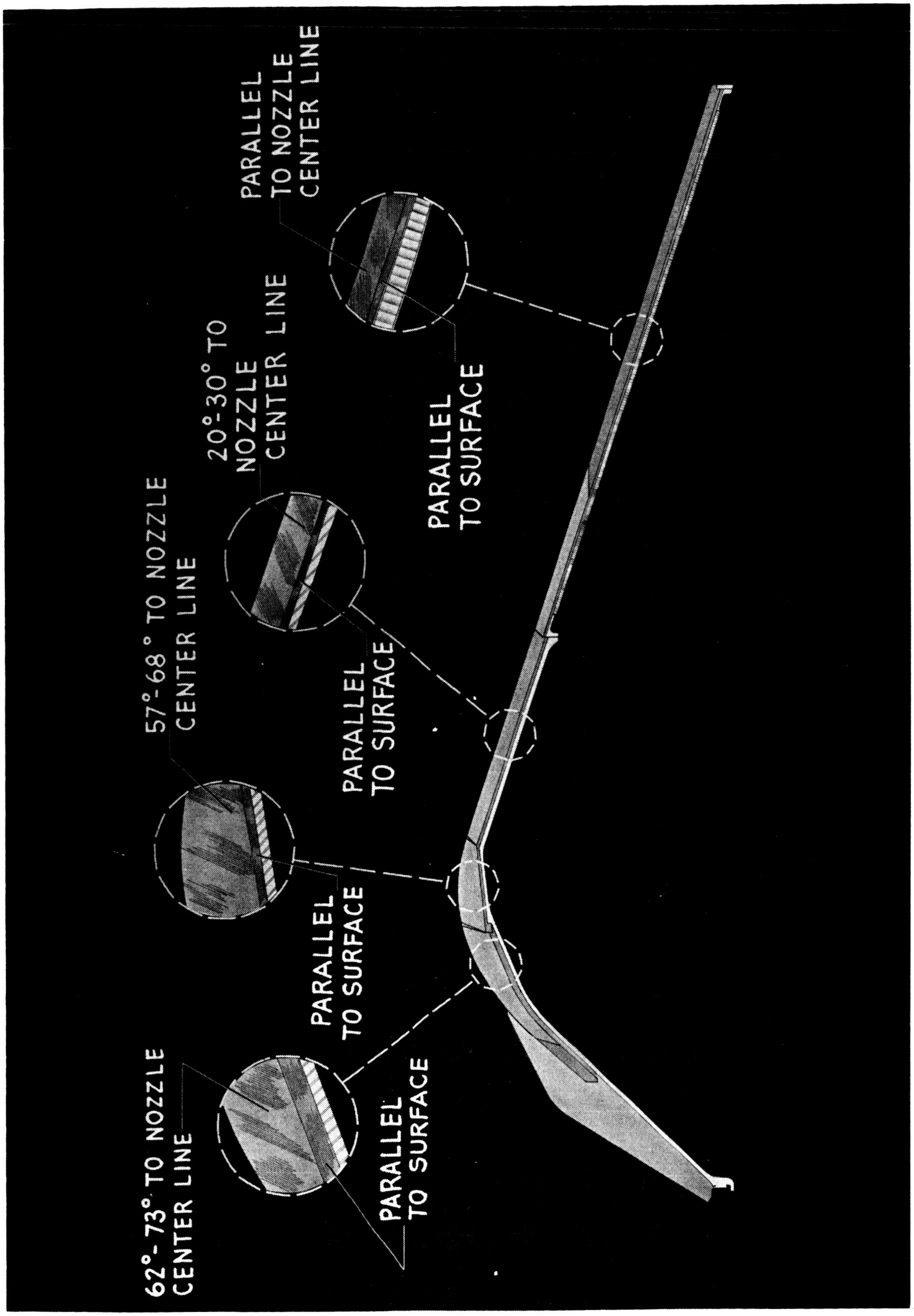
260-SL Motor Design

Figure 5



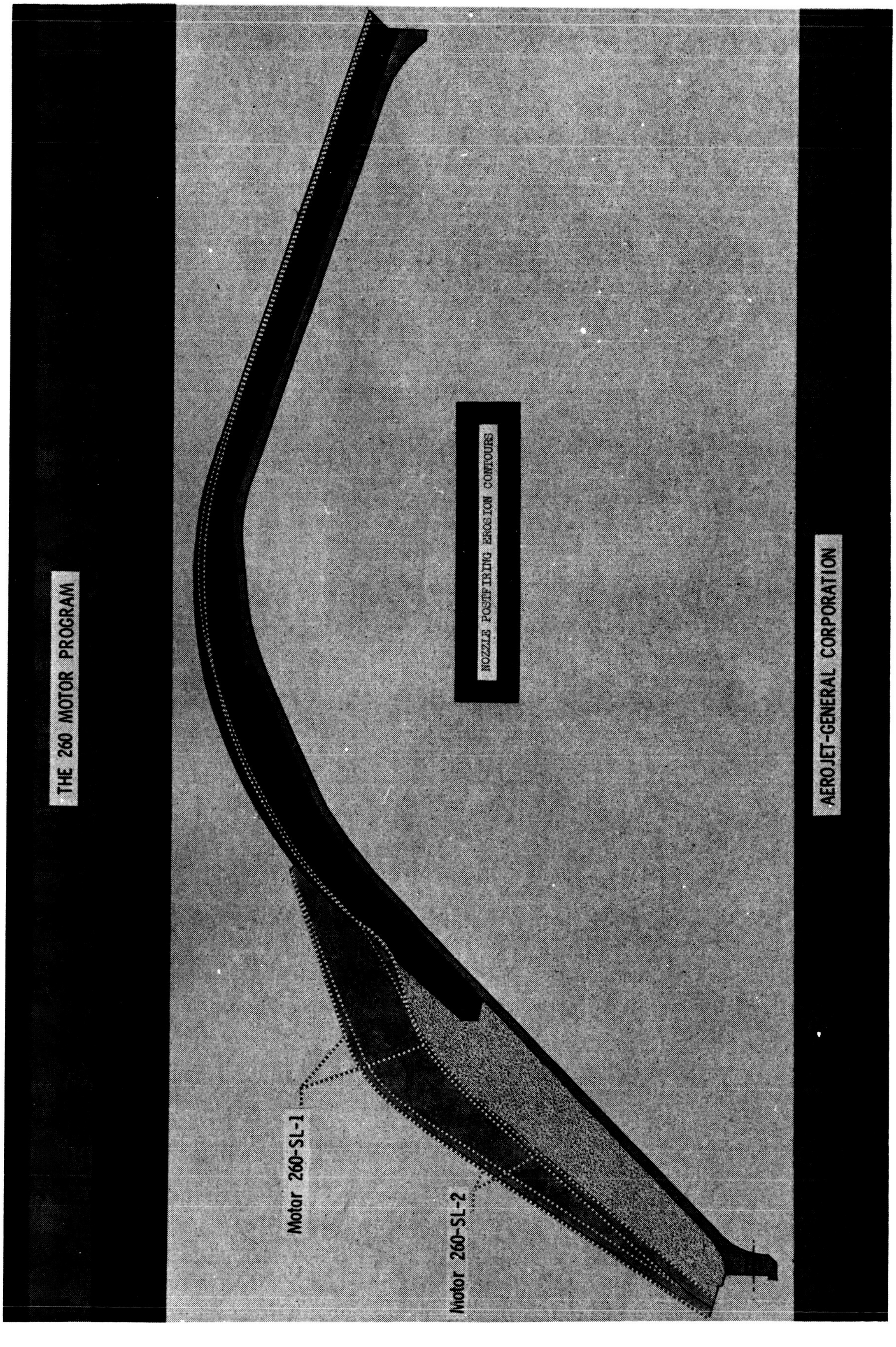
Nozzle Design, 260-SL Motors

Figure 6



Nozzle Material Orientations

Figure 7

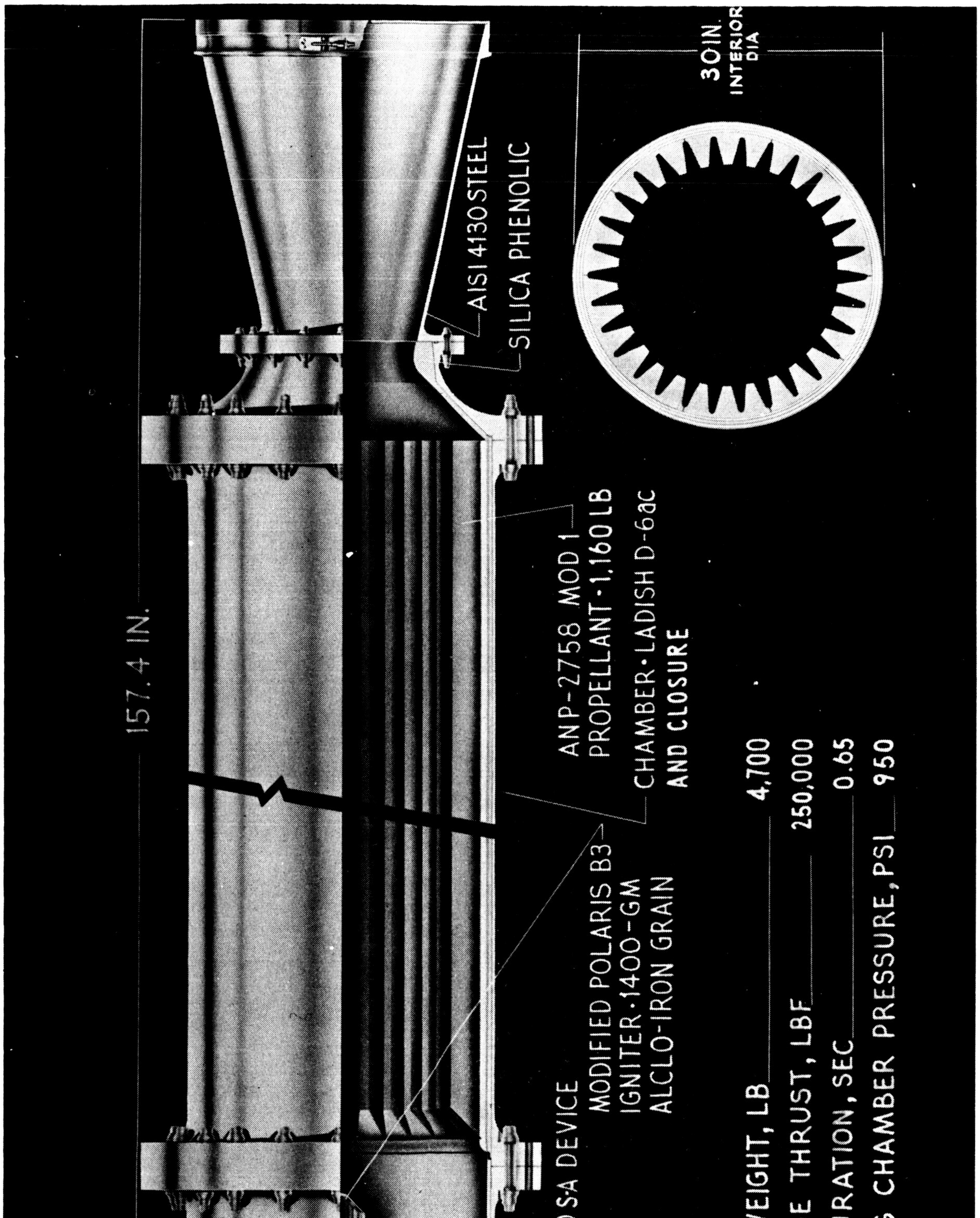


Prefiring and Postfiring Nozzle Erosion Contours

Figure 8

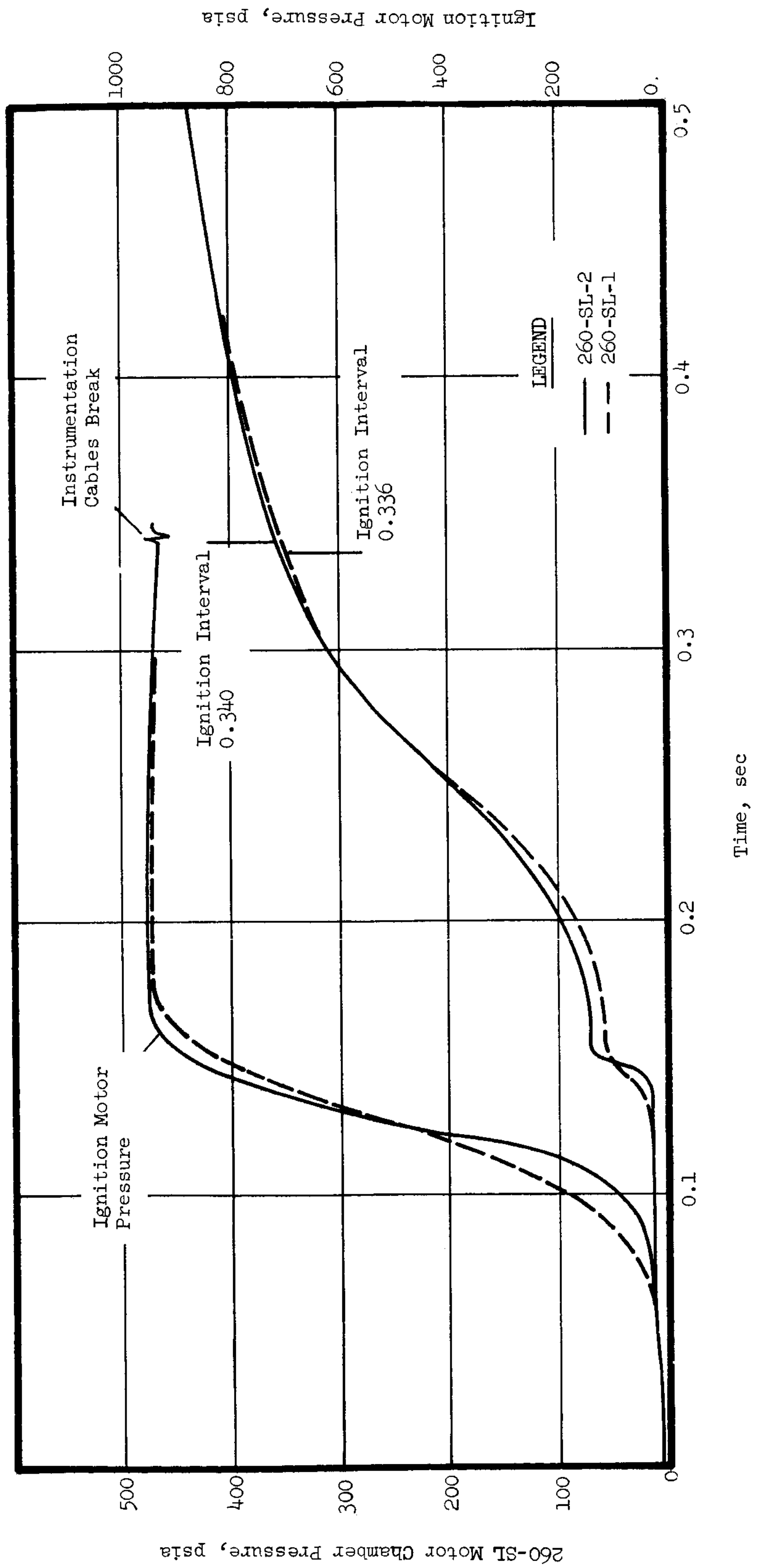
Prefiring View of Test Setup, Motor 260-SL-2

Figure 9



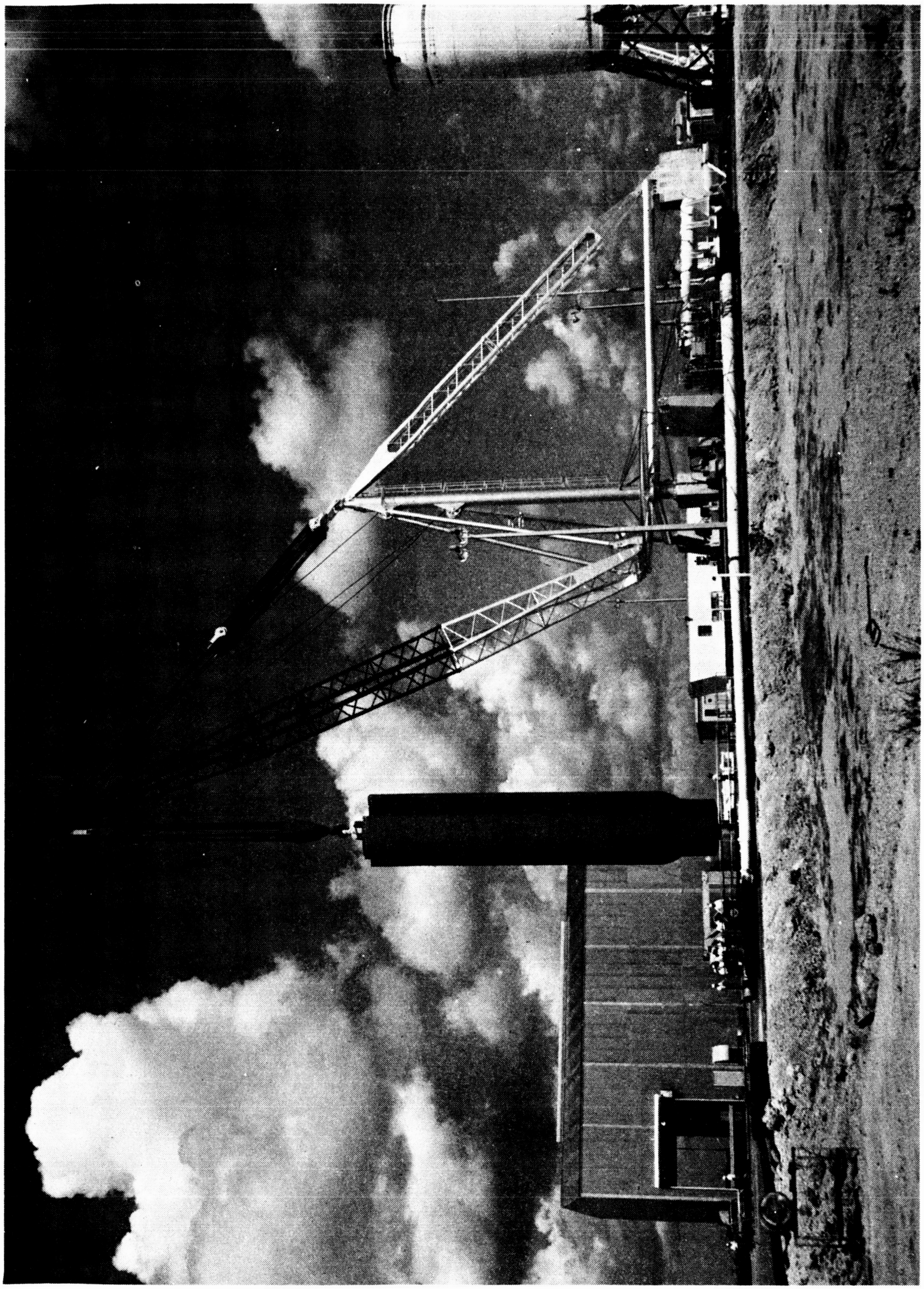
Igntion Motor Design

Figure 10



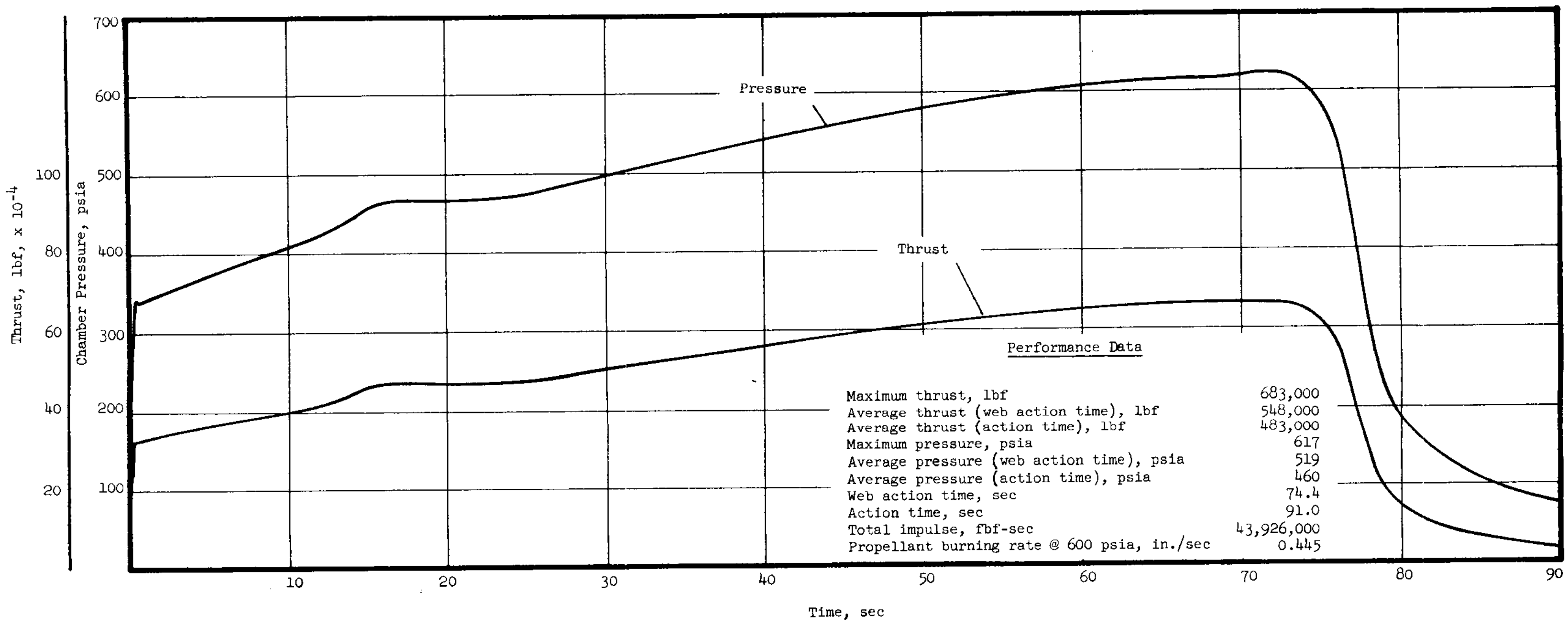
Ignition Performance of 260-SL Motors

Figure 11



Assembled Core for the 260-SL Motors

Figure 12



Pressure- and Thrust-vs-Time Curves, Motor 120-SS-1

Figure 13

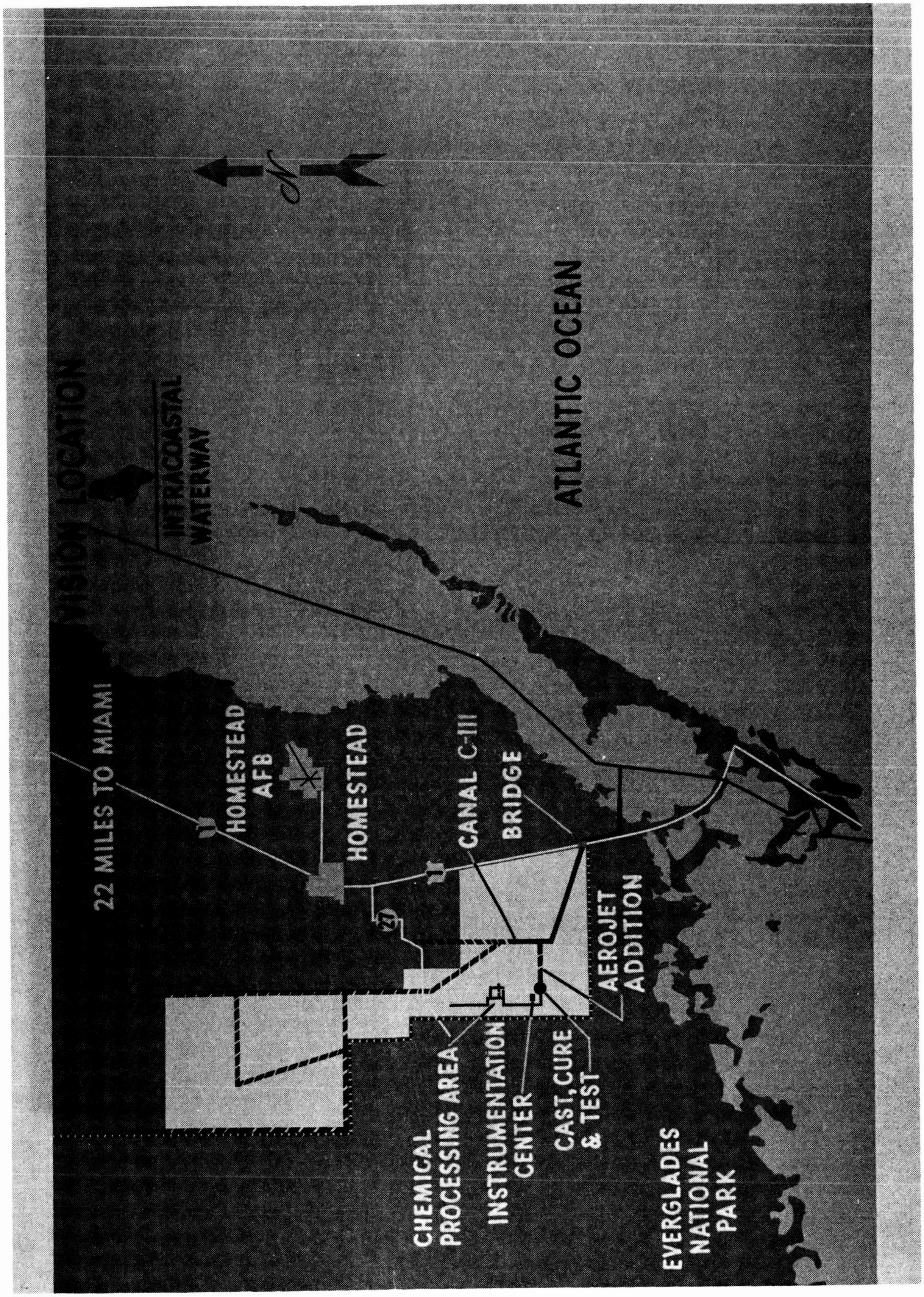

22 MILES TO MIAMI
HOMESTEAD AFB
HOMESTEAD
CANAL C-III
BRIDGE
AEROJET ADDITION
CHEMICAL PROCESSING AREA
INSTRUMENTATION CENTER
CAST, CURE & TEST
EVERGLADES NATIONAL PARK
INTRACOASTAL WATERWAY
ATLANTIC OCEAN
N

Figure 14

	Motors	
	260-SL-1	260-SL-2
Chamber fabrication started	20 Mar 64	1 June 64
All-welded chamber	22 Dec 64	28 May 65
Chamber proof tested	10 Mar 65	14 Aug 65
Chamber shipment	16 Mar 65	27 Aug 65
Chamber arrival at A-DD	31 Mar 65	15 Sept 65
Start installation of insulation	7 April 65	27 Sept 65
Complete installation of insulation	8 May 65	27 Oct 65
Start propellant casting	4 June 65	29 Nov 65
Complete propellant casting	15 June 65	9 Dec 65
Nozzle shell shipment from Sun Shipbuilding	27 April 65	27 Aug 65
Nozzle shell arrival at TRW	29 April 65	30 Aug 65
First nozzle insert bonded in shell	12 May 65	11 Nov 65
Exit cone liner wrapping started	1 Mar 65	9 Sept 65
Nozzle insulation bonded in shell	7 July 65	23 Dec 65
Nozzle and exit cone shipment from TRW	23 Aug 65	24 Jan 66
Nozzle and exit cone arrival at A-DD	2 Sept 65	5 Feb 66
Motor firing	25 Sept 65	23 Feb 66

Major Program Milestones, 260-in.-dia Motor Feasibility Demonstration Program

Figure 15